A Comparison between Perfectly and Imperfectly Competitive Downstream Electricity Markets under the Effect of Upstream Fuel Market Price

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Abstract

Upstream fuel markets can affect the production strategies of power producers, and further the market equilibrium, as well as the social welfare. In this paper, we present a study on the impacts of fuel price on electricity market in perfect and imperfect competitive environments. The differences between the power producers' strategies, and benefit transference among different market participants under the effect of fuel price are investigated and compared. It is found that fuel-dependent power producers' production responses with respect to the fuel price are similar in these two competition markets, but the incentives are very different. Moreover, the production strategies of non-fuel-dependent power producers have different effects on the fuel producer's profit. In addition, we show that the essence of the upstream fuel market's impact on the social welfare in the downstream electricity market is benefit transference among the producers, as well as between the producers and consumers.

***Index Terms*—upstream fuel market, downstream electricity market, fuel price, Cournot competition, perfect competition.**

I. INTRODUCTION

The goal of restructuring of the electric power industry is to introduce market competition to improve the overall economic efficiency.

The upstream fuel market is important to the downstream electricity market and its impact varies with different levels of market competition, e.g., a perfect versus an imperfect competition. The price variation in the upstream fuel markets directly affect the cost of electricity production, and possibly causing changes of the strategies of electricity producers. These strategies are also affected by the type of market competition.

Some researchers have studied the impact of fuel price on the electricity market. For example, Balogun [1] and Gutierrez [2] study the impact of fuel price on electricity tariffs and the spot market respectively. Cunningham [3] focuses on the outcomes in perfect competition as a benchmark studying utilities' best responses in an imperfectly competitive market without consideration for the effect of fuel price. Marzooni [4] proposes a simulation model studying investment decisions in the presence of either a perfect or imperfect electricity market, without taking into consideration of the effect of fuel price. To our understanding, there is no specific comparison and study on the market under perfect and imperfect competition explaining the impacts of fuel price.

Comparing the impact of fuel price on social welfares in either a perfect or imperfect competition market could help improve our understanding of the market equilibrium. Many researchers focus on the social welfare problem. For example, Chaitusaney [5] and Wu [6] studied the social welfare maximization problem. Huang [7] and Ryan [8] studied on how social welfare is affected within their frameworks.

Motivated by the fact that there are few studies on analyzing the impact of fuel price on social welfare, particularly benefit transference among different market participants, we conduct a comparison study on a perfectly and imperfectly competitive market based on a model where we consider the effect of the upstream fuel market. In particular, this paper attempts to analyze power producers' strategies and benefit transference among different market participants under the effect of fuel price.

The paper is organized as follows. In Section II we present the model with consideration of the upstream fuel market. Section III presents and explains the simulation results in both perfectly and imperfectly competitive markets. Section IV concludes.

II. MODELS

In this section, a linkage model is presented in order to describe the upstream fuel market and downstream electricity market where the linkage is the fuel price. It is assumed that there is one fuel producer in the upstream fuel market and there are three power producers with different generation technologies in the downstream electricity market. Three power producers are denoted as *HE*, *LE*, and *RE*: *HE* represents the group of fuel-dependent power producers using high efficiency generation technology (with low heat rate[1]); *LE* represents the group of fuel-dependent power producers but using low efficiency generation technology (with high heat rate); *RE* represents the group of non-fuel dependent power producers (using renewable generation technology).

A. Cost Models

The cost models for power producers and the fuel producer are classified into two types according to the dependency on the fuel. For the fuel-dependent power producers, the main costs are

[1] Heat rate is a typical measurement used in the energy industry to calculate how efficiently a generator uses heat energy. It can be used to represent the electricity production cost excluding the impact of the fuel.

spent on fuel, so we only consider the fuel cost for this type of power producer. The fuel cost is generally represented as a quadratic function under a given fuel price. Since the fuel price proportionally affects the fuel cost, the cost model for each fuel-dependent power producer is:

$$Cost_i = P_{fuel}(\alpha_i Q_i^2 + \beta_i Q_i + \gamma_i) \quad i \in \{HE, LE\} \tag{1}$$

where $Cost_i$ is the cost for fuel-depend power producers, P_{fuel} is the fuel price, α, β and γ are coefficients, and Q_i is the amount of electricity production. The heat rate of *HE* is lower than that of *LE*; $\alpha_{HE} < \alpha_{LE}$ and $\beta_{HE} < \beta_{LE}$.

The cost model is further assumed to be linear for the non-fuel-dependent power producers:

$$Cost_{RE} = \beta_{RE} Q_{RE} \tag{2}$$

where $Cost_{RE}$ is cost of the non-fuel-dependent power producer, and β_{RE} is the cost coefficient of *RE*. We assume that *RE* has capacity limit C_{RE}, since otherwise the other power producers, *HE* and *LE* will be out of the market. We discuss our market scenario in more detail in Section III.

We use a simple linear cost model is also assumed for the fuel producer:

$$Cost_{fuel} = c_{fuel} P_{fuel} \tag{3}$$

where c_{fuel} is fuel producer's marginal production cost.

B. Demand Model

Demand function is a behavioral relationship between the quantity consumed and a consumer's maximum willingness to pay for incremental increases in quantity. This is usually a linearly inverse function:

$$P_e = \theta - \rho \sum_{j \in J} Q_j \quad J \in \{HE, LE, RE\} \tag{4}$$

where P_e is the electricity price, and θ and ρ are coefficients. J is a set of power producers including *RE*.

C. Social Welfare

Social welfare measures the amount of happiness for both consumers and producers. It is the summation of consumer and producer surplus.

Consumer surplus is a measure of the economic welfare enjoyed by consumers, as a proxy for consumer happiness. Consumer surplus is calculated as the difference between what consumers are willing to pay relative to the market price:

$$ConsumerSurplus = \int_0^{Q_{total}} P_e(Q)\,dQ - P_e(Q_{total})Q_{total} \quad Q_{total} = \sum_{j \in J} Q_j \tag{5}$$

Producer surplus is a measure of the economic welfare enjoyed by firms or producers. Producer surplus is calculated as the difference between the power producers' revenue and the cost to produce all of the supplied electricity:

$$ProducerSurplus = P_e(Q_{total})Q_{total} - \sum_{j \in J} Cost_j \tag{6}$$

The social welfare is therefore expressed by the summation of consumer surplus and producer surplus as they are shown in equation (5) and (6):

$$SocialWelfare = \int_0^{Q_{total}} P_e(Q)\,dQ - \sum_{j \in J} Cost_j \tag{7}$$

III. CASE STUDY

A. Results in Perfect Competition

In this section we present the simulation results for a perfectly competitive market. The competitive results calculated as the results of maximization of social welfare where generation groups are bidding based on their true costs and benefits.

1) Power Producers' Production Related to the Market Clearing Fuel Price

The levels of power production from *HE*, *LE*, and *RE* in a perfectly competitive environment with respect to the fuel price are plot in Fig. 1. The production level reflects the best response of each producer to the change in fuel price, which is different for individual producer due to their different dependency on fuel:

- RE's production is limited at its capacity level is shown as the green line in Fig. 1 due to its capacity limit. Although it is independent from fuel and therefore has a cost advantage compared to other producers, its capacity limits give it no better choice but to produce up to its capacity limit.
- *HE* and *LE* will reduce their production level when the fuel price goes up shown as the red line (*HE*) and blue line (*LE*) in Fig. 1 due to their dependency on fuel price. When fuel price increases their marginal costs must also increase; they must reduce their production to decrease their marginal costs and meet the current electricity price. *LE*'s production level is also lower than that of *HE* due to its lower efficiency or high production cost. And *LE* becomes out of market when the fuel price is at the point of "a" in Fig. 1 where *LE* does not produce electricity anymore because of the higher fuel price.

2) Fuel Producer's Profit Function with Respect to Fuel Price

The fuel producer's profit is primarily affected by the fuel price and fuel demand consumed by *HE* and *LE*. We show its profit function with respect to the fuel price in a perfectly competitive market in Fig. 2:

The curve trend is that before the vertex (the highest point in the curve) the profit is monotonously increasing with fuel price, while after the vertex, the profit is monotonously decreasing with fuel price. When the fuel price is at a low level (lower than that in the vertex), the fuel producer knows that fuel-dependent power producers can accept a bit slightly higher fuel price without significantly reducing their production levels. The profit earned by the fuel producer by charging higher fuel prices will be greater than that suffered by demand loss. When the fuel price is at a high level (higher than that in the vertex) the fuel dependent power producer may even exit the market if the fuel producer charges more. Charging a higher price will accordingly make the fuel producer suffer profit loss.

The decreasing trend in the inflection point of "a" is slowed. This point represents the beginning of Region II in Fig. 1. After this point "a" *LE* exits the market, reducing the fuel producer's profit compared to the previous situation where both *HE* and *LE* reduce production simultaneously.

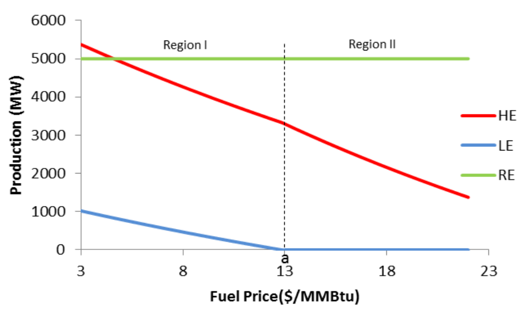

Fig. 1: The best responses of electricity producers to the fuel price.

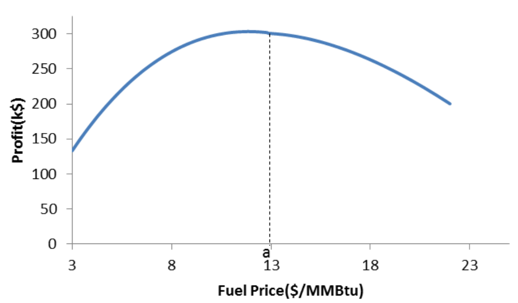

Fig. 2: Fuel producer's profits compared to the fuel price.

The fuel price in the vertex is accordingly the optimal choice for a fuel producer in the market equilibrium.

B. Results in Imperfect Competition

In this subsection B, we present simulation results in the imperfectly competitive market in this section. The imperfect competition is assumed to be a Cournot competition where each power producer chooses the optimal production in order to maximize its profit, assuming its rivals keep their productions constant.

1) Best Strategies for Power Producers with Respect to Fuel Price in Market Equilibrium

Along with the increase in the fuel price, market conditions in the imperfectly competitive market will also change and can be described using three behavior regions as shown in Fig. 3. Power producers' best responses in each market regions are described in the following:

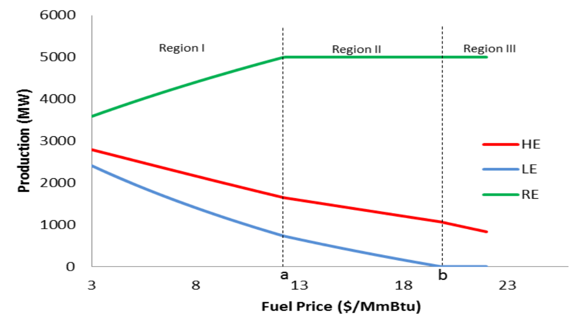

Fig. 3: The electricity producers' best responses to the fuel price.

Region I: The area in the left side of Fig 3 represents a low fuel price condition in the upstream market. Since the marginal costs of fuel-dependent power producers are not much higher than those of the renewable power producer, under such a low fuel price level each generation group has the opportunity to produce electricity. *RE* has a cost advantage, and therefore does not need to withhold its production as much as other power producers do; its production level is always the highest. On the other hand, *LE* must withhold more compared to *RE* and *HE*. *HE* and *LE* will reduce their production levels in response to a higher fuel price because their marginal costs will increase, while *RE* will raise its production level because *HE* and *LE* will transfer their market shares to RE.

Region II: The fuel price level in this region is higher than that in Region I but lower than that in Region III shown in Fig 3. The fuel price in this region is not so high that *LE* and *HE* survive in the market, but *RE* hits its capacity. *RE* will no longer strategically compete with *HE* and *LE*. For the fuel-dependent power producers this indicates that although their best responses to the rising fuel price are still withholding their production levels for the same reason explained in Region I, they have lower inclination in this region to withhold their production compared to Region I. The slopes of *HE* and *LE*'s best response accordingly become smaller compared to Region I.

Region III: The fuel price level in this region is the highest among all the regions shown in the right of Fig. 3. Under such a high fuel price the market condition will be that *LE* will exit the market, *RE*'s production is still constrained by its capacity, and only *HE* has strategies responding to the fuel price. Note that unlike the Region II, *HE* has higher inclination to further withhold its production. When *LE* is out of the market no one could help *HE* maintain the electricity price, so *HE* must withhold more compared to the region where *LE* still exists in the market.

2) Fuel Producer's Profit

The profit curve in the imperfect competition market shown in Fig. 4 is similar to that under perfect competition; however, they still have differences. Under imperfect competition the profit curve's inflection point is greater than that under perfect competition by one due to *RE*'s strategies. Although *RE* has the cost advantage, under perfect competition, it is still a price taker and must produce up to its capacity. However, under imperfect competition, *RE* can either strategically withhold its production or produce up to its capacity. There is accordingly one additional inflection point under imperfect competition. Note that the fuel price in the vertex is accordingly the optimal choice for a fuel producer within the market equilibrium.

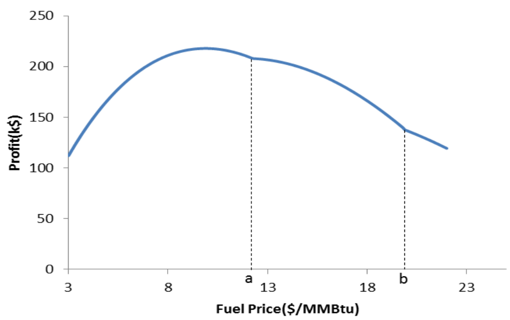

Fig. 4: Fuel producer's profits compared to the fuel price.

C. Comparison of Social Welfare between Imperfectly and Perfectly Competitive Markets

In this section, the results under perfect and imperfect competition are compared in term of consumer surpluses, producer surpluses, and social welfare.

1) Consumer Surpluses

We show the comparison of consumer surpluses under both perfect and imperfect competition in Fig. 5, where the blue line represents the perfectly competitive market and the red line demonstrates the imperfectly competitive market:

The consumer surplus under perfect competition is larger than that under imperfect competition for a given fuel price. This indicates that electricity consumers receive greater benefit under perfect competition versus imperfect competition. Electricity consumers will be happier if electricity producers compete with each other in a perfect competition manner than in the imperfect case.

The consumer surplus is monotonously decreasing in both competition markets in response to increasing fuel price. This is because the marginal producer's costs, whether *HE* or *LE*, increases in both competition markets when the fuel price increases. The electricity price will increase under this effect and the consumer surplus will decrease under both competition types. This means that any increase in fuel price will hurt consumers' happiness and transfer part of consumers' benefits to electricity producers.

The consumer surplus will decrease more under perfect competition versus imperfect competition when the fuel price increases. Although fuel-dependent power producers will reduce their productions, when the fuel price increases *RE* has different responses in these two markets. Under a perfectly competitive market, *RE* can only maintain its production levels due to its capacity constraints, while under the imperfect competition market it can either produce more electricity or maintain its production. In this case the increased electricity price in an imperfect competition market will be less than that in a perfect competition market when the fuel price increases, particularly when the fuel price is at a low level such that *RE*'s best response to an increasing fuel price is producing more electricity.

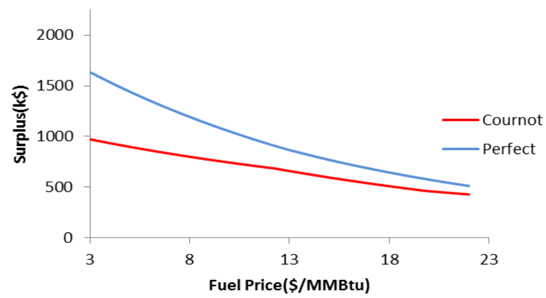

Fig. 5: Consumer surpluses for cournot and perfect competition.

2) Producer Surpluses

In Fig 6, the comparison of producer surpluses under both perfect and imperfect competition is shown, where the blue line represents a perfectly competitive market and the red line demonstrates the imperfectly competitive market:

The producer surplus in an imperfectly competitive market is larger than that of a perfectly competitive market. This indicates that electricity producers are receiving greater benefits under imperfect versus perfect competition. We find that when electricity producers compete with each other in an imperfect competition manner then the electricity producers will be happier than in the perfect case.

Producer surplus has different trend of change with respect to fuel price in these two competition markets. In the imperfectly competitive market producer surplus is slightly decreasing first, and then increases with fuel price shown using the red line in Fig. 7; under perfect competition the producer surplus continues increasing with fuel price shown as the blue line in Fig. 7. This phenomenon is highly related with the amount of benefits transferred from customers. As we have explained above, under perfect competition the benefit transferred from consumers to producers is greater that in an imperfect market such that the increased benefit allows producers to acquire so much additional profit that even the fuel producer will gain some from producers. However, producers within imperfectly competitive market do not have the same advantage. When the fuel price is at the low level where the producer surplus decreases with the fuel price, then the fuel producer's benefit has a soaring increase transferred from the fuel producers shown in Fig. 4 before the vertex. Although power producers gain some benefit from consumers, it is not enough to compensate for the loss transferred to the fuel producers. The producer surplus therefore slightly decreases in this situation. It will be improved when fuel price continues increasing until the fuel producer's benefit begins decreasing after the vertex as shown in Fig. 4. The producer surplus will then begin to increase.

Producers suffer less benefit loss under imperfect than perfect competition when the fuel price increases. This can be explained via the similar reason we used to explain consumer surplus.

3) Social Welfare

The differences in terms of social welfare are compared under perfect and imperfect competition in Fig 7 where the blue line represents the perfectly competitive market and the red line demonstrates the imperfectly competitive market:

The social welfare under perfect competition is greater than that under imperfect competition. This indicates that the electricity market participants are receiving greater benefits under perfect versus imperfect competition. If electricity producers compete with each other in a perfect competition manner then the total amount of happiness will be larger than in the imperfect case.

The social welfare decreases with the increasing fuel price. The reduced social welfare primarily consists of two parts: benefits transferred to the fuel producer and benefit losses caused by low production. This indicates that any increase in fuel price will hurt the total power industry's happiness; part of this is transferred to the upstream fuel industry and the remainder is lost due to low economic efficiency.

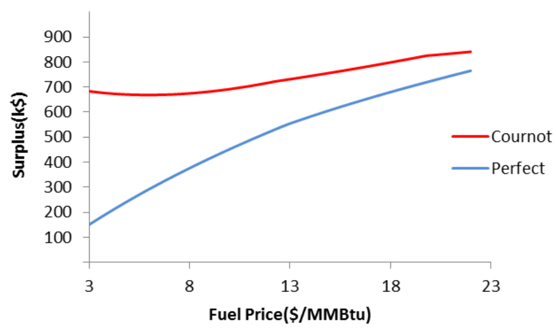

Fig. 6: Cournot and perfect competition consumer surpluses.

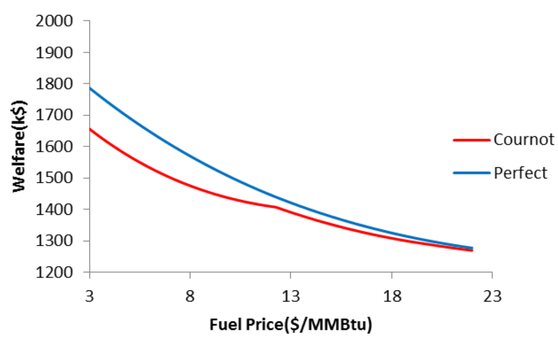

Fig. 7: Social welfare of Cournot and perfect competition.

IV. CONCLUSIONS

We conduct a comparison study between perfect and imperfect competition. More specifically, we compare the impact of the upstream fuel market on power producers' production as well as the social welfare in two competition markets.

We find that fuel-dependent power producers' responses with respect to the fuel price are similar in these two competition markets, but the incentives are very different. Moreover, the production strategies of non-fuel-dependent power producers have different effects on the fuel producer's profit. In addition, we show that the essence of the upstream fuel market's impact on the social welfare in the downstream electricity market is benefit transference among the producers, as well as between the producers and consumers. A higher fuel price can hurt the consumers' benefit, but benefits power producers as well as the fuel producer. The increased benefits obtained by the fuel producer and power producers are transferred from consumers. On the other hand, these higher fuel prices will hurt power industry on the whole. In addition, the social welfare under perfect competition is greater than that under imperfect competition and the fuel price's degree of impact on a perfectly competitive market is greater than that on an imperfectly competitive market.

V. REFERENCES

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